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Neotectonics of the Offshore Oak Ridge Fault near Ventura, Southern California

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Abstract The Oak Ridge fault is a large-offset, south-dipping reverse fault that forms the south boundary of the Ventura Basin in southern California. Previous research indicates that the Oak Ridge fault south of the town of Ventura has been inactive since 200–400 ka ago and that the fault tip is buried by $\sim$ 1 km of Quaternary sediment. However, very high-resolution and medium-resolution seismic reflection data presented here show a south-dipping fault, on strike with the Oak Ridge fault, that is truncated at 80 m depth by an unconformity that is probably at the base of late Pleistocene and Holocene sediment. Furthermore, if vertically aligned features in seismic reflection data are eroded remnants of fault scarps, then a subsidiary fault within the Oak Ridge system deforms the shallowest imaged sediment layers. We propose that this subsidiary fault has mainly left-slip offset. These observations of Holocene slip on the Oak Ridge fault system suggest that revision of the earthquake hazard for the densely populated Santa Clara River valley and the Oxnard coastal plain may be needed.

Introduction

The Oak Ridge fault extends east–west for about 130 km through the onshore Ventura and the offshore Santa Barbara sedimentary basins (Fig. 1, lower left inset), where it forms a major basin-bounding fault (Yeats, 1988; Yeats *et al.*, 1988; Sorlien *et al.*, 2000). This fault poses a substantial earthquake hazard; Yates (1988), for example, estimated that since 200–400 ka ago, vertical displacement along an onshore part of this fault accumulated at 5.9–12.5 mm/yr. Furthermore, this fault may be the westward continuation of the fault system responsible for the 1994 *M* 6.7 Northridge earthquake (Yeats and Huftile, 1995).

We investigate the neotectonics of the offshore Oak Ridge fault south of the town of Ventura, using seismic reflection data collected during the summer of 2000 by the U.S. Geological Survey (Fig. 1, tracklines). Shallow geologic structure is revealed by very high-resolution, chirp, and Huntec-minisparker data and by medium-resolution data collected with a small (17 in^3) airgun.

Geologic Setting

The Ventura and Santa Barbara Basins lie within the east–west Transverse Ranges province, which cuts perpendicularly across the regional, north and northwest structural grain of major faults and mountain ranges elsewhere in southern California. The province ends to the south along the Santa Monica Mountains and the Channel Islands (Fig. 1, lower left inset). These physiographic features are thought to be uplifted along deep-seated north-dipping thrust faults (Dolan *et al.*, 2000; Shaw and Suppe, 1994). The study area includes part of the shallow (< 50 m), low-relief continental shelf south of Ventura, which is the westward continuation of the Oxnard plain. This plain marks the western end of the high topography of the Santa Monica Mountains (Fig. 1, lower left inset).

Since the late Pliocene, about 4 Ma ago, the study region has undergone strong north–south compression (Yeats *et al.*, 1988; Yeats and Huftile, 1995; Sylvester and Brown, 1997; Sorlien *et al.*, 2000). A Global Positioning System (GPS) survey revealed an ongoing north–south shortening rate across the Ventura Basin of 7–10 mm/yr (Donnellan *et al.*, 1993).

The Oak Ridge fault dips steeply (60–80°) south, extends downward to a decollement at about 8 km depth, and forms the Ventura Basin's south boundary (Yeats, 1983, 1988; Yeats *et al.*, 1988; Huftile and Yeats, 1995) (Fig. 1, lower right inset). The town of Saticoy (Fig. 1, lower left inset). marks the approximate juncture between eastern and western segments of this fault. In the east near South Mountain, fault displacement since 200–400 ka ago amounts to 2.5 km and occurred at high rates (5.9–12.5 mm/yr) (Yeats, 1988).

West of Saticoy, however, fault displacement occurred during the middle Pleistocene, but since 200–400 ka ago, this displacement has been essentially zero (Yeats *et al.*, 1988; Huftile and Yeats, 1995; Azor *et al.*, 2002). According

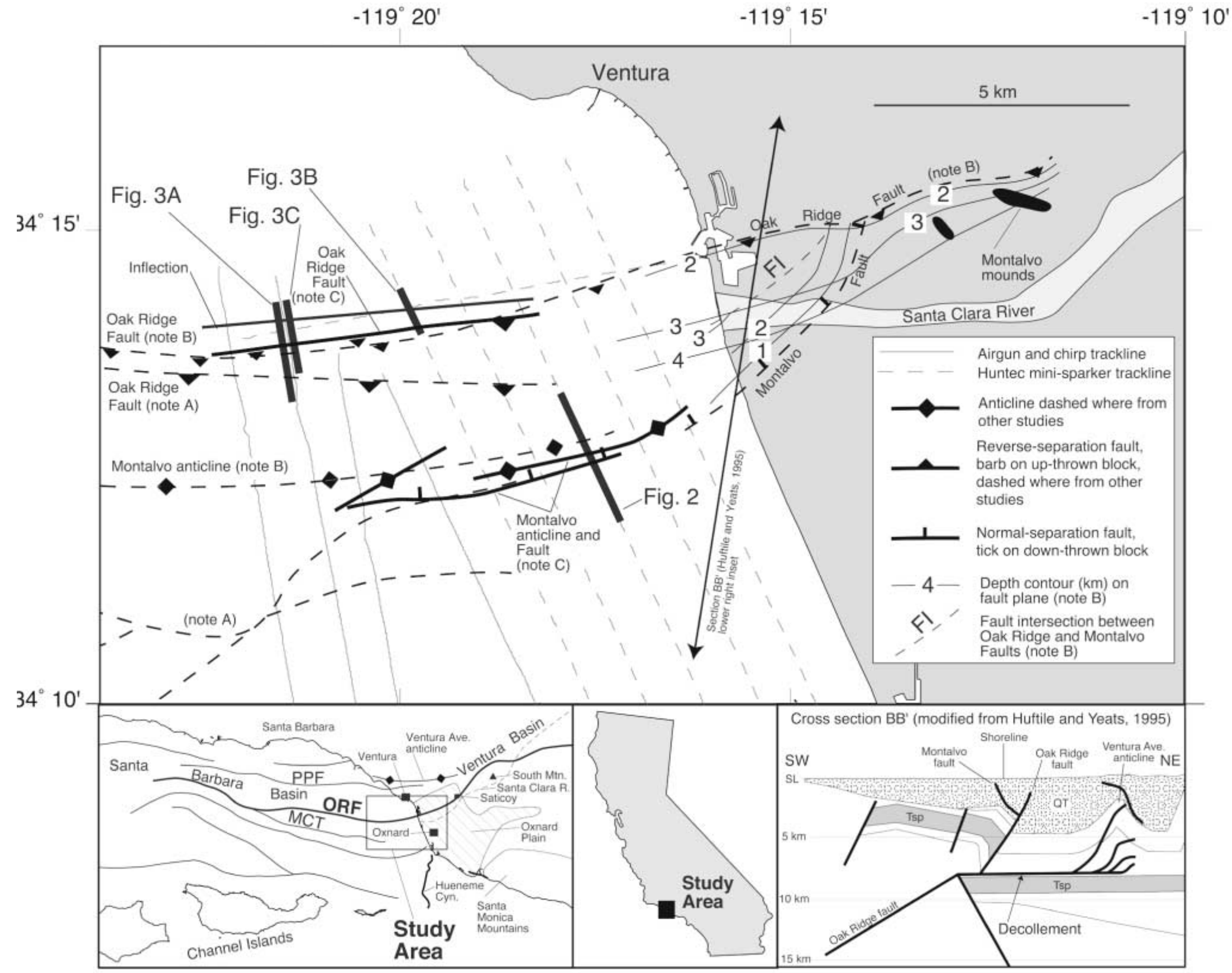

Figure 1. Study area location, tracklines of seismic reflection data, and geologic structure. In the lower left inset, PPF is Pitas Point Fault; ORF is Oak Ridge fault; MCT is Mid-Channel trend. In the lower right inset, Tsp denotes the Oligocene Sespe Formation; QT indicates the late Pliocene and Pleistocene section of the Fernando Formation, the "Mudpit Shale," and the Saugus Formation (see Huftile and Yeats, 1995). (note A) In the western part of the study area, the location of the Oak Ridge fault and other faults is where they cut a seismic horizon near the top of the Monterey Formation (Heck, 1998). (note B) The locations of the onshore Oak Ridge and Montalvo faults are from Yeats *et al.* (1998); the location of the Montalvo anticline is from Greene *et al.* (1978) and Yeats (1988). (note C) Location of offshore structures, including the Oak Ridge and Montalvo faults and the Montalvo anticline, derived in this study, are where these features cut an unconformity probably at the base of late Pleistocene and Holocene strata.

to an analysis of the Ventura basin using balanced structural cross sections, below the line of section BB′ (Hultile and Yeats, 1995) (Fig. 1, lower right inset; section location shown in Fig. 1) the tip of the Oak Ridge fault is buried by Quaternary sediment 1250 m thick (Yeats *et al.*, 1982). Recent displacement along the western fault segment has been transferred eastward from the Oak Ridge fault along a decollement at ~ 8 km depth, and this displacement has been taken up by the Ventura Avenue anticline (Yeats, 1988; Yeats *et al.*, 1988; Huftile and Yeats, 1995) (Fig. 1, lower right inset).

Apparently, recent movement along the western segment of the Oak Ridge fault has not ceased entirely, as indicated by the Montalvo mounds (Fig. 1). These features are short-wavelength (150–300 m) pressure ridges, perhaps cored by shallow thrust faults, that approximately overlie the buried tip of the Oak Ridge fault and indicate recent left slip (Hall, 1982; Yeats *et al.*, 1982; Yerkes *et al.*, 1987).

Offshore Geology

Previous Research

Seismic reflection data indicate that beneath the continental shelf west of the Oxnard plain, an extensive low-relief unconformity separates about 80 m of upper Pleistocene and Holocene deposits, above, from Pleistocene rocks and sediment, below (Greene *et al.*, 1978; Dahlen *et al.*, 1990; Dahlen, 1992). The age of this unconformity is based on a comparison of the offshore stratigraphy with sediment penetrated in onshore wells (Greene *et al.*, 1978) and on a seismic stratigraphic analysis (Dahlen *et al.*, 1992). The Santa Clara River (Fig. 1) is the primary sediment source to the offshore area, and during late Quaternary low stands in sea level, this river and the Hueneme submarine canyon (Fig. 1) were linked to transport sediment southward from the Ventura basin to deep-water areas. A point important to the interpretation of seismic reflection data is that the river repeatedly meandered across the Oxnard plain and adjacent offshore shelf.

The Oak Ridge fault has been identified in seismic reflection data as a wide (~2 km) zone of deformed strata and, less commonly, as an array of sharp breaks (Dahlen, 1992). This fault was traced 11 km west of the coast to where it became obscured within sediment having poor seismic reflectivity (Green *et al.*, 1978; Dahlen, 1992). The unconformity at the base of upper Pleistocene and Holocene deposits showed a maximum vertical separation of 17 m along the Oak Ridge fault, and the separation decreased eastward toward shore (Dahlen, 1992).

This Study's Findings

Seismic reflection data collected for this study show the extensive low-relief unconformity at the base of upper Pleistocene and Holocene sediment (Fig. 2). Above the unconformity, reflections are mainly horizontal and discontinuous, most likely because the deposits tend to be sandy and were deposited in the delta plain near the Santa Clara River mouth (Fig. 1). In contrast, strata below the unconformity produce reflections that are more continuous, perhaps reflecting marine deposition. These deeper strata are deformed by faults and anticlines.

The unconformity truncates most underlying geologic structures, including the anticline in the middle of Fig. 2. This anticline strikes east (Fig. 1) and correlates with the Montalvo anticline (Greene *et al.*, 1978; Yeats, 1983; Yeats *et al.*, 1988; Dahlen *et al.*, 1990). A fault associated with the anticline (Fig. 2) also strikes east and very likely connects with the onshore Montalvo fault (Fig. 1), which is a north-dipping normal fault (Yeats, 1988, 1998; Huftile and Yeats, 1995). The dip and sense of throw of the onshore and offshore faults match.

The unconformity marks an abrupt decrease in vertical separation along the offshore part of the Montalvo fault (Fig. 2, inset). Below the unconformity, this separation amounts to 10–12 m (for a 1600 m/sec average sediment velocity). The unconformity itself is offset by 3–4 m, and a short distance above the unconformity, seismic reflections appear to extend unbroken across the fault's tip.

Small-airgun seismic section 811 shows numerous strong diffractions, from below the unconformity (Fig. 3A), that reveal a south-dipping fault. This fault is located along strike of the onshore Oak Ridge fault. The airgun data show clearly that the unconformity truncates the fault and, similarly, very high-resolution Huntec minisparker data (Fig. 3B, line 1854) show that the unconformity extends unbroken across the fault's tip.

In seismic reflection data obtained north of the Oak Ridge fault, inflections (so labeled on Fig. 3A–C) are evident at many stratigraphic levels but especially in the unconformity. These inflections are vertically aligned and deeper on the north.

Discussion

Unlike results reported elsewhere, we recognize two offshore strands, possibly two generations, of the Oak Ridge fault. As described in the Previous Work section, Dahlen *et al.* (1992) reported a wide (~2 km) zone of distributed deformation associated with the Oak Ridge fault. In contrast, we focus on two features that together delimit a narrow fault zone. The first of these features causes the strong diffractions (Fig. 3A) that reveal what we call the main strand of the Oak Ridge fault. This strand dips south and ends updip at the unconformity. This fault strand was not described in previous work. The second feature we identify as a possible strand of the Oak Ridge fault connects the vertically aligned inflections. These aligned inflections appear to be what previous workers (Greene *et al.*, 1978; Dahlen *et al.*, 1992) identified as the Oak Ridge fault.

We extend the main strand of the Oak Ridge reverse fault upward to within 80 m of the seafloor; consequently in our view, instead of ceasing 200–400 ka ago, reverse movement along this fault continued until sometime during the late Pleistocene or early Holocene, when final unconformity cutting and initial burial occurred. A significant question we cannot answer fully concerns the amount of vertical offset along this fault strand—perhaps the Oak Ridge fault extended to shallow depth but had negligible offset. However, the numerous diffractions produced by this fault strand in small-airgun data (Fig. 3A) suggest that rocks on opposite sides of the fault differ considerably in acoustic impedance. We use this inferred impedance contrast as a proxy for fault offset to suggest that substantial fault movement occurred just before or while the unconformity was cut.

We propose that the second fault strand connects the vertically aligned inflections evident at several stratigraphic levels (Fig. 3A–C). If so, then this fault strand deforms sediment just under the seafloor, and the strand is active.

A possibility we favor is that this fault strand is related to the fault(s) involved in the deformation of the Montalvo mounds. These pressure ridges overlie the Oak Ridge fault

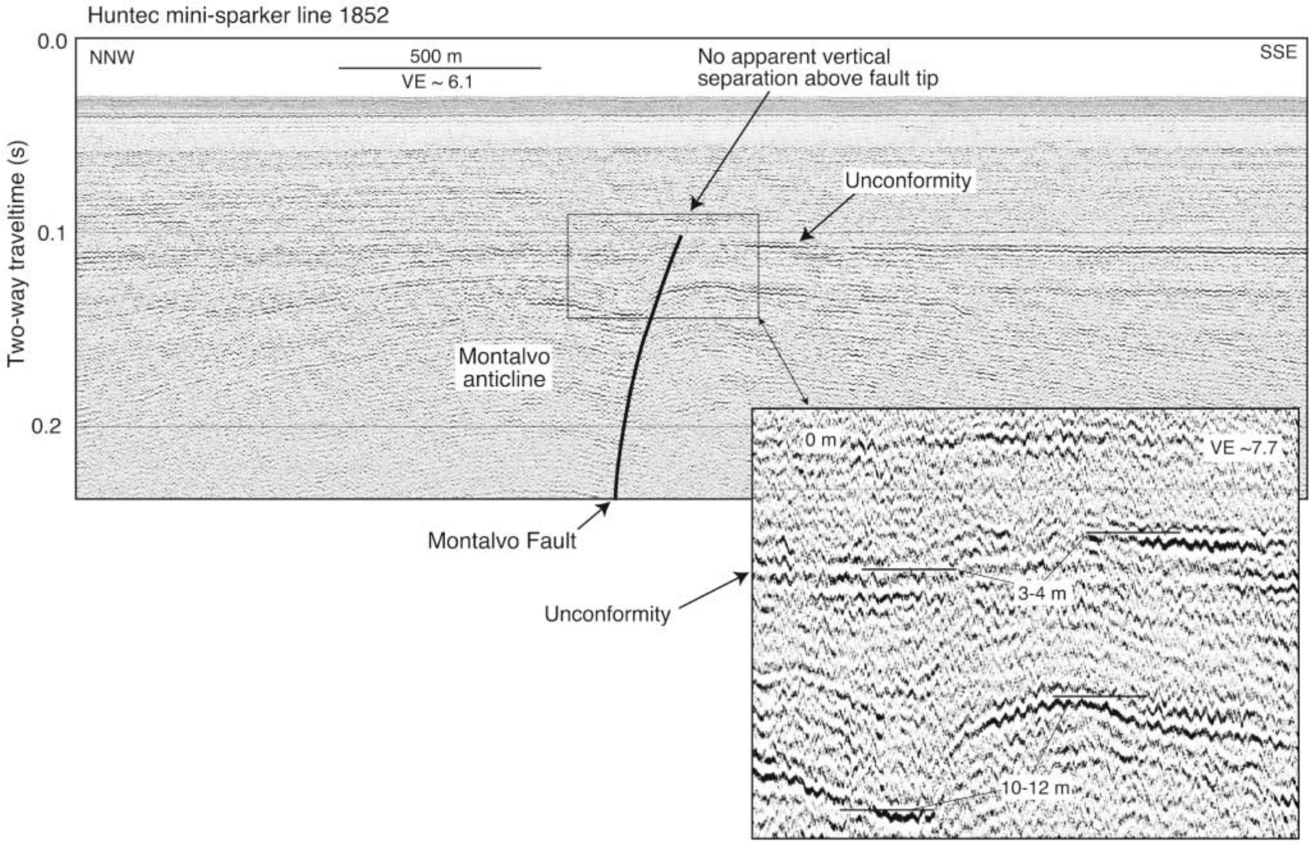

Figure 2. Huntec minisparker seismic section showing the Montalvo fault and anticline. Seismic section location is in Figure 1. The fault and anticline are truncated by an unconformity at a travel time of 0.1 sec (about 80 m depth) and probably at the base of late Pleistocene and Holocene strata. The inset detailed seismic section shows that this unconformity is offset 3–4 m by the Montalvo normal fault. Fault offset apparently diminishes to zero a short distance above the unconformity.

and indicate recent left or left-oblique slip on a shallow fault(s) (Hall, 1982). Perhaps no through-going connection ties the offshore fault strand with the one(s) near the mounds, but recent movement along the Oak Ridge fault system may involve left-slip along numerous fault splays.

The main difficulty with this interpretation is that the study area lies south and west of where the Santa Clara River debouches into the Santa Barbara Channel (Fig. 1); hence, the inflections might be scars left by meandering river channels. No oppositely facing inflections, representing the opposite sides of possible channels, are evident, however. Also, river channels tend to migrate laterally and are unlikely to remain vertically aligned like the inflections. In our view, the inflections represent fault scarps that were erosionally modified while exposed on the delta plain.

It is possible to measure the difference in height across the inflections (Dahlen *et al.*, 1992), upward through the postunconformity sediment section, to derive a rate of inflection development (about 1 mm/yr). However, the high likelihood that the Santa Clara River eroded this area continuously during the late Quaternary makes such a number an unreliable indicator for the accumulation rate of vertical fault separation.

We propose that two generations of the Oak Ridge fault deform offshore rocks and sediment. The unconformity at the base of late Pleistocene and Holocene deposits clearly bevels the main fault strand and the Montalvo anticline. These structures show no sign of reactivation. In our interpretation, deformation during the fault's younger generation includes possible left slip along the fault indicated by the inflections.

If our suppositions are correct, then ongoing shallow strike-slip movement occurs along the Oak Ridge fault system, which bears critically on the assessment of the regional earthquake hazard. Yeats (1988) explained that even if the shallow, steeply dipping part of the Oak Ridge reverse fault is inactive near the coast, a substantial earthquake threat still exists because a major earthquake could occur along the deep (~8 km) decollement (Fig. 1, lower right inset). We suggest further that during a major deep earthquake, shallow fault movement and ground breakage could occur along one or more strike-slip faults, like the one we identified. A more

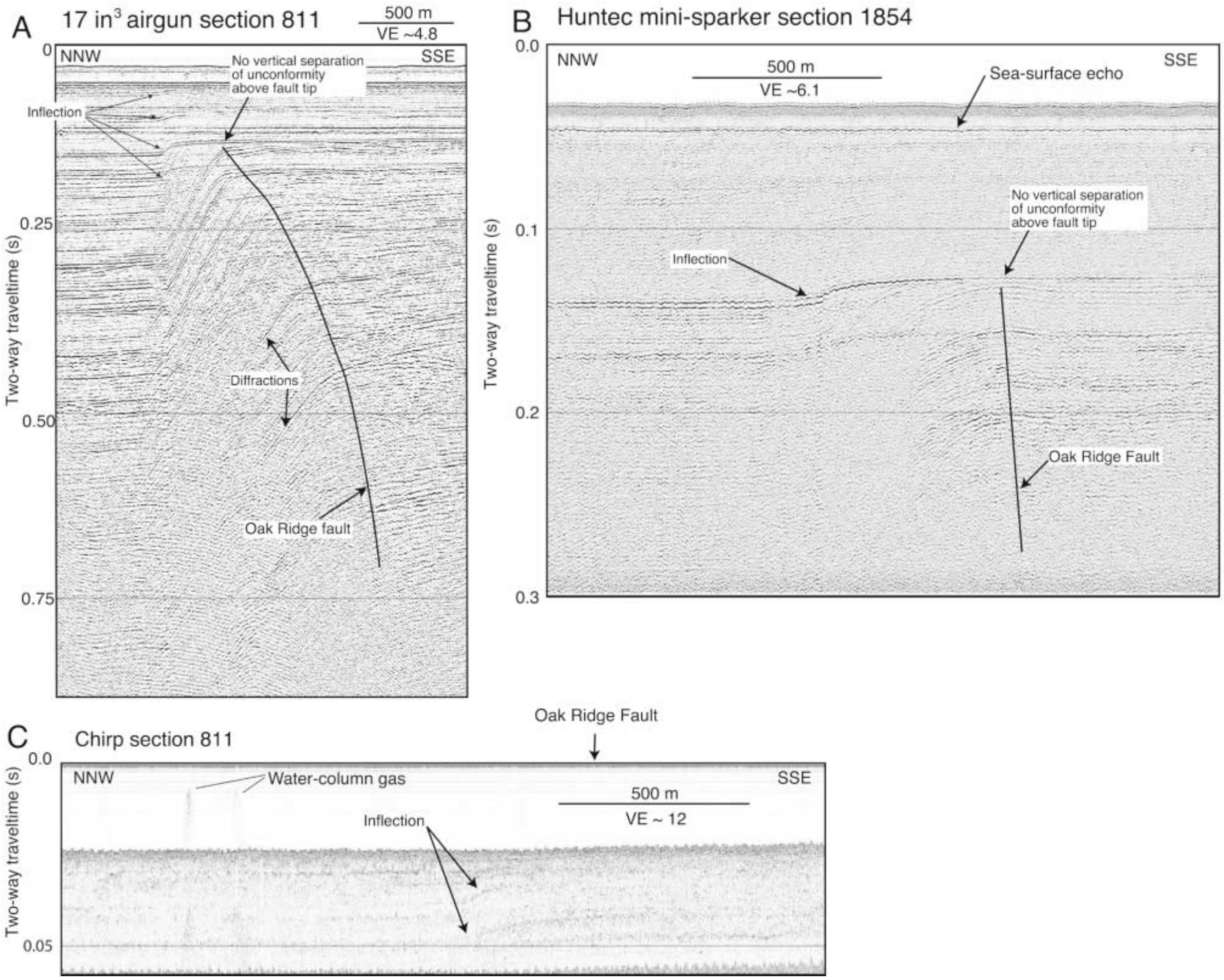

Figure 3. (A) Small-airgun seismic section over the offshore Oak Ridge fault, showing the fault's south dip and strong diffractions generated by truncated beds. The unconformity is probably at the base of late Pleistocene and Holocene strata and is not offset vertically by the fault. Section location is shown in Figure 1. (B) Huntec minisparker section over the Oak Ridge fault, showing that the unconformity is not offset along the fault. Section location is shown in Figure 1. (C) Chirp seismic section over the Oak Ridge fault showing no apparent offset of strata at shallow depths. Section location is shown in Figure 1. In all parts of this figure, the ambiguous feature labeled "Inflection" affects the unconformity and extends upward to within a short distance of the seafloor. This feature probably signifies a subsidiary but active fault within the Oak Ridge system.

remote possibility is that the main reverse fault truncated at the unconformity could sustain renewed shallow activity.

Conclusion

The last movement on what we call the main strand of the Oak Ridge fault occurred at shallow (80 m) depth during the late Pleistocene or early Holocene. Subsequently, fault movement seems to have occurred along a vertical strike-slip fault. If validated, our suggestion about recent offset along this fault would make the regional earthquake threat more acute for the densely populated Santa Clara River valley and the Oxnard plain.

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